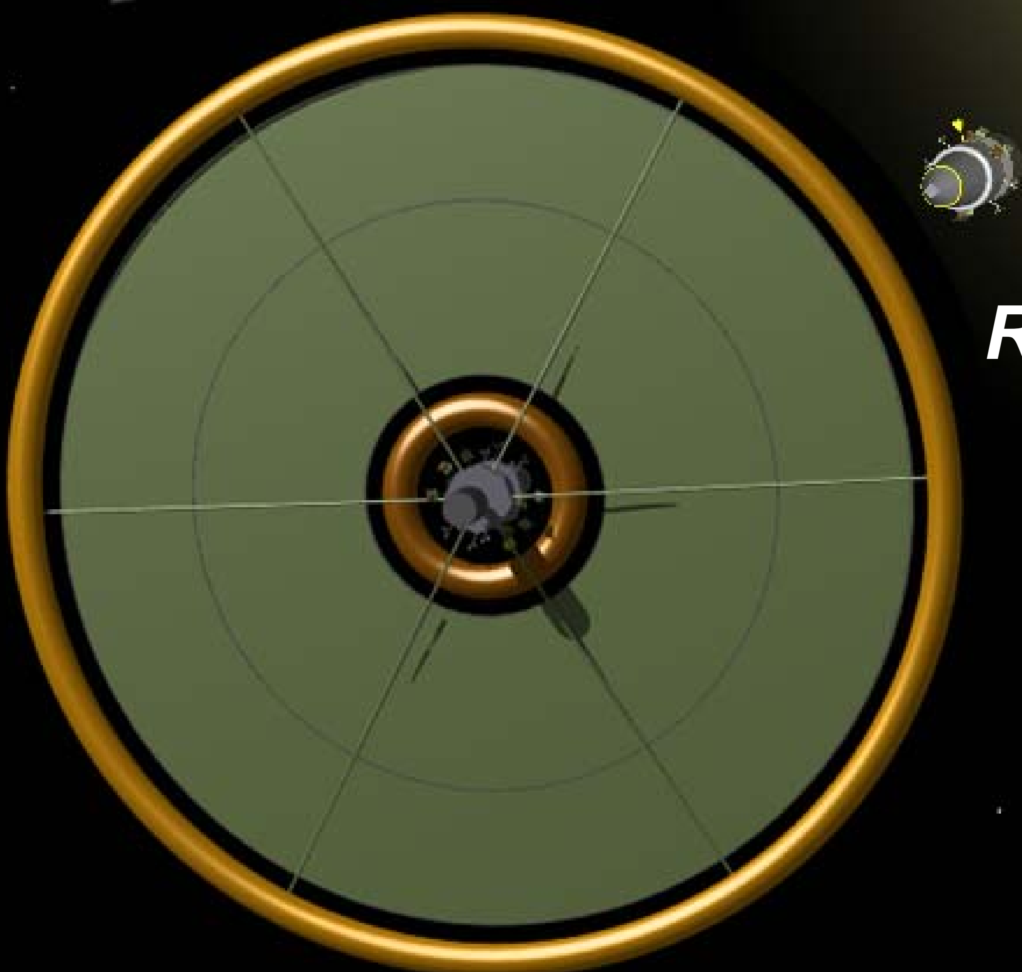


RASC Space Theme 2: Science From New Perspectives

Earth Atmosphere Observatory at L2

Dr. Joseph Zawodny
Jeffrey Antol
March 16, 2004

Background

- Atmospheric Remote-Sensing Observatory at the L2 Lagrange point (Joseph Zawodny – LaRC)
- Virtual Structure Gossamer Space Telescope (Edward Mettler – JPL)

- **Study Approach:**
  - The "Virtual Structure Gossamer Space Telescope" selection serves as the focal point while the "Atmospheric Remote-Sensing Observatory at the L2 Lagrange Point" selection provides the science requirement drivers

- **Objectives**
  - Develop a concept for an Earth observing capability at Earth-Sun L2
  - Define the science to be conducted and the associated instrumentation
  - Develop conceptual designs for the instrument, telescope, and supporting spacecraft
  - Define an end-to-end mission architecture
  - Assess the technical challenges and identify enabling technologies

Science Objectives

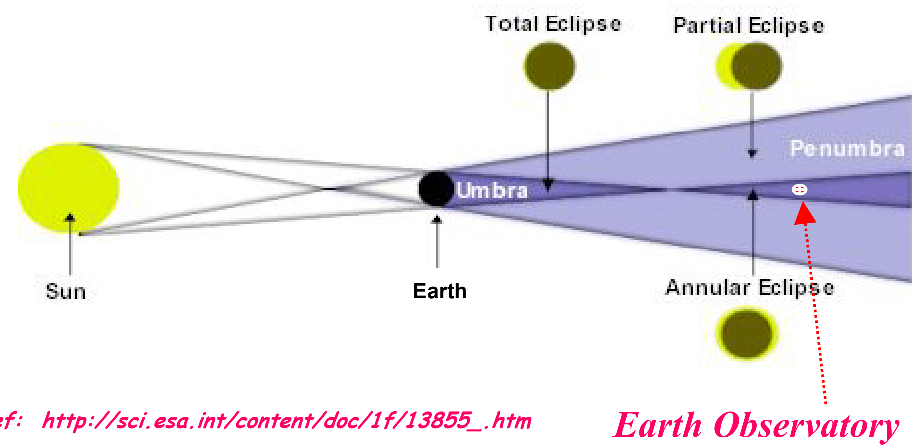
- Monitor changes in the Forcing and Response of the Earth's Atmosphere
- Understand the mechanisms of change and quantify the attribution of change be it of chemical or dynamical origin
- Improve the short and long term predictive capability of weather and climate models through the use of near real time measurements and an improved understanding of the dynamical, chemical, radiative Feedbacks and Responses of the Climate System

Measurement Objectives

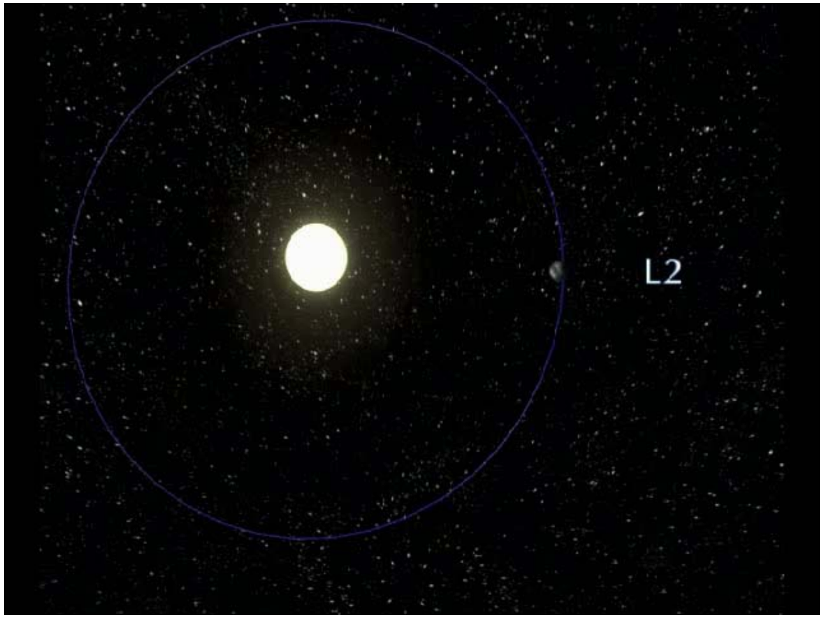
Measurement Approach

- **Use the solar occultation technique for trend-quality measurements on decadal time scales.**
- **Locate observatory near the Earth-Sun L2 Lagrange point to obtain continuous coverage with high spatial resolution/sampling.**
- **Nearly continuous spectral coverage from 0.38 to 10.0 microns (μm) from at least 3 instruments.**
- **Utilize the dense sampling with tomographic or stereographic techniques to improve horizontal resolution.**

Observatory Orbit



Ref: http://sci.esa.int/content/doc/1f/13855_.htm

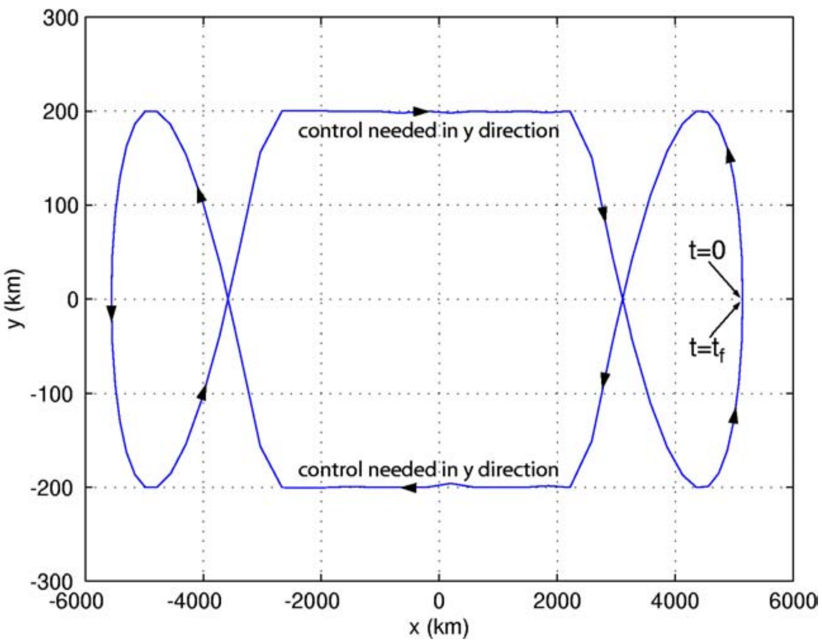


- **Powered "orbit" near L2 to maintain observatory position within the annular eclipse**
  - **Must stay within 200 km of the Sun-Earth line**
- **"Standard" orbits won't work**
  - **Lissajous and halo orbits stray far from Sun-Earth line**
  - **Nearly rectilinear halo orbits are perpendicular to line between primaries, and don't account for 4th body perturbation**

Minimum Fuel Periodic Orbit at Earth Sun L_2

- **Must stay within 200 km of the Sun-Earth line, however, cyclic drift of +/- 5000 km *along* the Sun-Earth line is allowed to reduce propellant requirements**

- **Without the "candy wrapper" orbit, a 10 year mission is not possible without the resupply of propellant**



- References:

Shen, H., Kumar, R. R., and Seywald, H., "Minimum-Fuel Periodic Orbits in the Vicinity of a Fixed Point on the Sun-Earth Line: The Planar Case," AAS 04-247, 14th AAS/AIAA Space Flight Mechanics Meeting, Maui, Hawaii, Feb. 8--12, 2004

Roithmayr, C. M., and Kay-Bunnell, L., "Keeping a Spacecraft on the Sun-Earth Line," AAS 04-246, 14th AAS/AIAA Space Flight Mechanics Meeting, Maui, Hawaii, Feb. 8--12, 2004.

Science Comparison

Item	LEO*	GSFC-L2	RASC-L2
Science Objectives	Broad Range	Age of Air Low Res Dynamics	Climate Forcing Climate Response Forecast Model Input Lowest Strat Dynamics Upper Trop Composition Age of Air Strat-Trop Exchange
Vertical Resolution	0.5 to 2.0 km	2 to 4 km	1 km
Vertical Range	2 to 100 km	8 to 30 km	8 to 100 km
Altitude Knowledge	50 to 200 m	1000 m	100 m
Latitude Sampling	1 to 5 deg	> 0.5 deg	0.25 to 1 deg
Longitude Sampling	1 to 24 deg	< 15 deg (sparse)	0.25 to 1 deg
Global Maps	0 to 2 per Day	0 to 2 per Day	2 per Day
Continuous Mapping	Yes	No	Yes
Profiles per Day	30 to 200,000	est < 15,000	160,000 to 2,000,000
Duty Cycle (monthly Avg)	6 to 100%	est ~20% ??	100%

* LEO instruments include HiRDLS, HALOE, MLS, SAGE, ACE-FTS

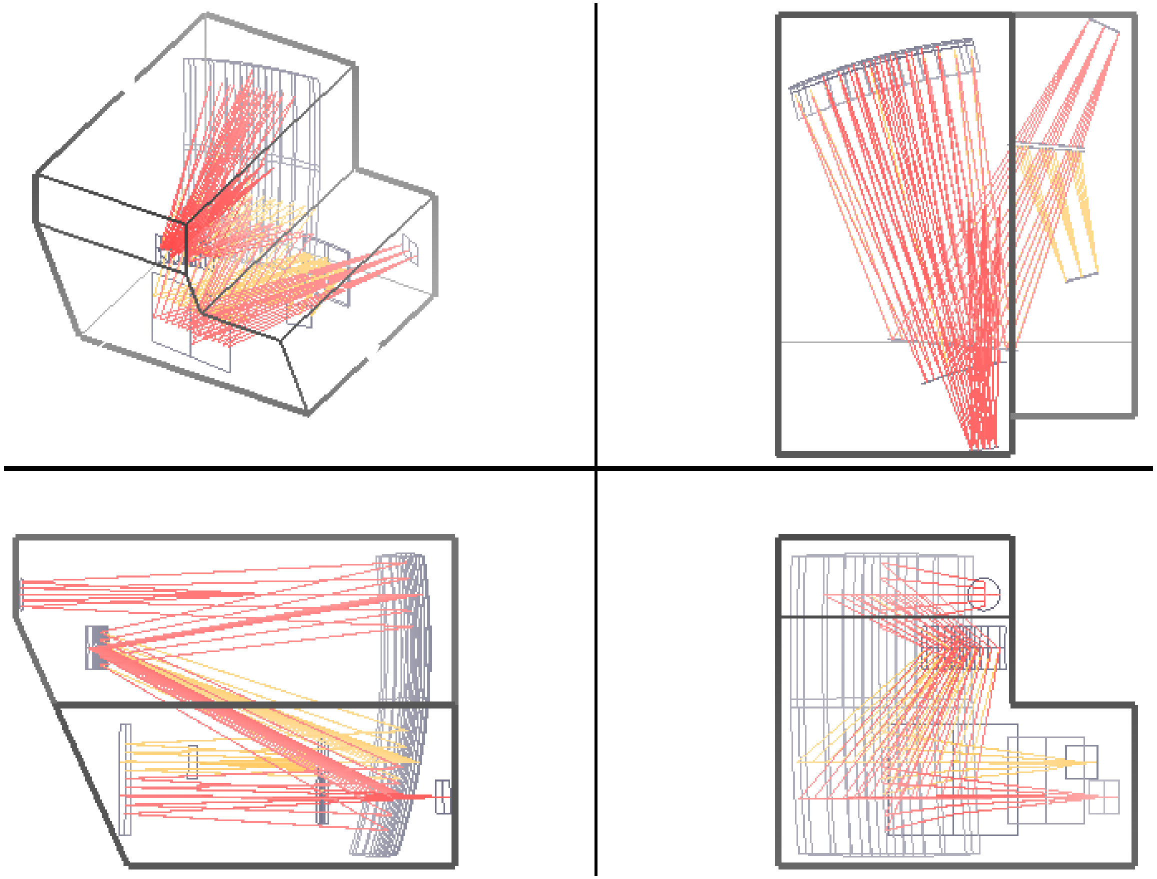
Science Comparison (cont)

Item	LEO*	GSFC-L2	RASC-L2
Spectral Range	0.2 to 500 µm	1 to 4 µm	0.38 to 10 µm
Measurement SNR	500 - 2000	500	4000
O_3, H_2O, CO_2, CH_4, N_2O, O_2	Yes	Yes	Yes
NO_x, ClO_x, HO_x	Yes	No	Yes
NO_x, ClO_x, HO_x Sources / Reservoirs	Yes	No	Yes
Temperature & Pressure	Yes	Yes	Yes
Aerosols	Yes	No	Yes
Sulfate/Water/Ice/NAT/…	Yes	No	Yes
Needs	Multiple Platforms, Instruments, & Techniques	Increased Sampling Larger Aperture	Technology Advance

* LEO instruments include HiRDLS, HALOE, MLS, SAGE, ACE-FTS

Design Drivers

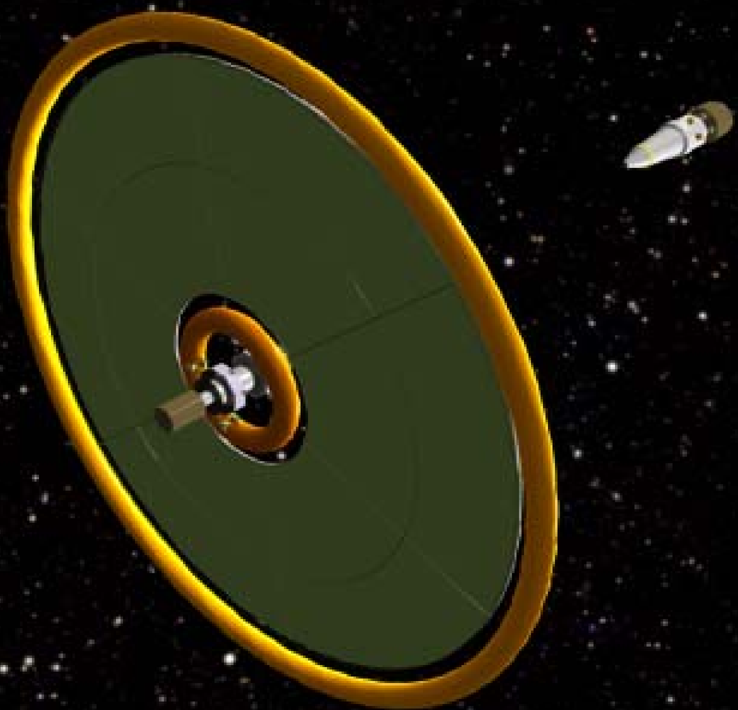
- Spectral coverage from 0.38 to 10µm:
  - Employ at least three instruments covering the Visible, NIR, & Mid-IR
- Radiometric performance to support sampling
  - 0.5 seconds per profile measurement
  - 25 meter diameter filled aperture
- Pointing knowledge:
  - Coarse Pointing derived from Sun & Earth limb
  - Fine pointing derived from profiles of O_2
- Stringent Jitter control – No Moving Parts:
  - Spectrometers must image the annulus radially
  - Passive cooling



Theoretical Concerns

- **Forward Scattering vs. Direct Solar: Is Limb Scattering a significant interference or a scientific plus for determining particle phase & composition?**
- **What are the effects of small scale waves on altitude registration and vertical resolution**
- **Development and validation of algorithms for simple retrievals and tomography prior to launch**
- **High spatial variability within solar Fraunhofer lines and their impact on species and aerosol retrievals**

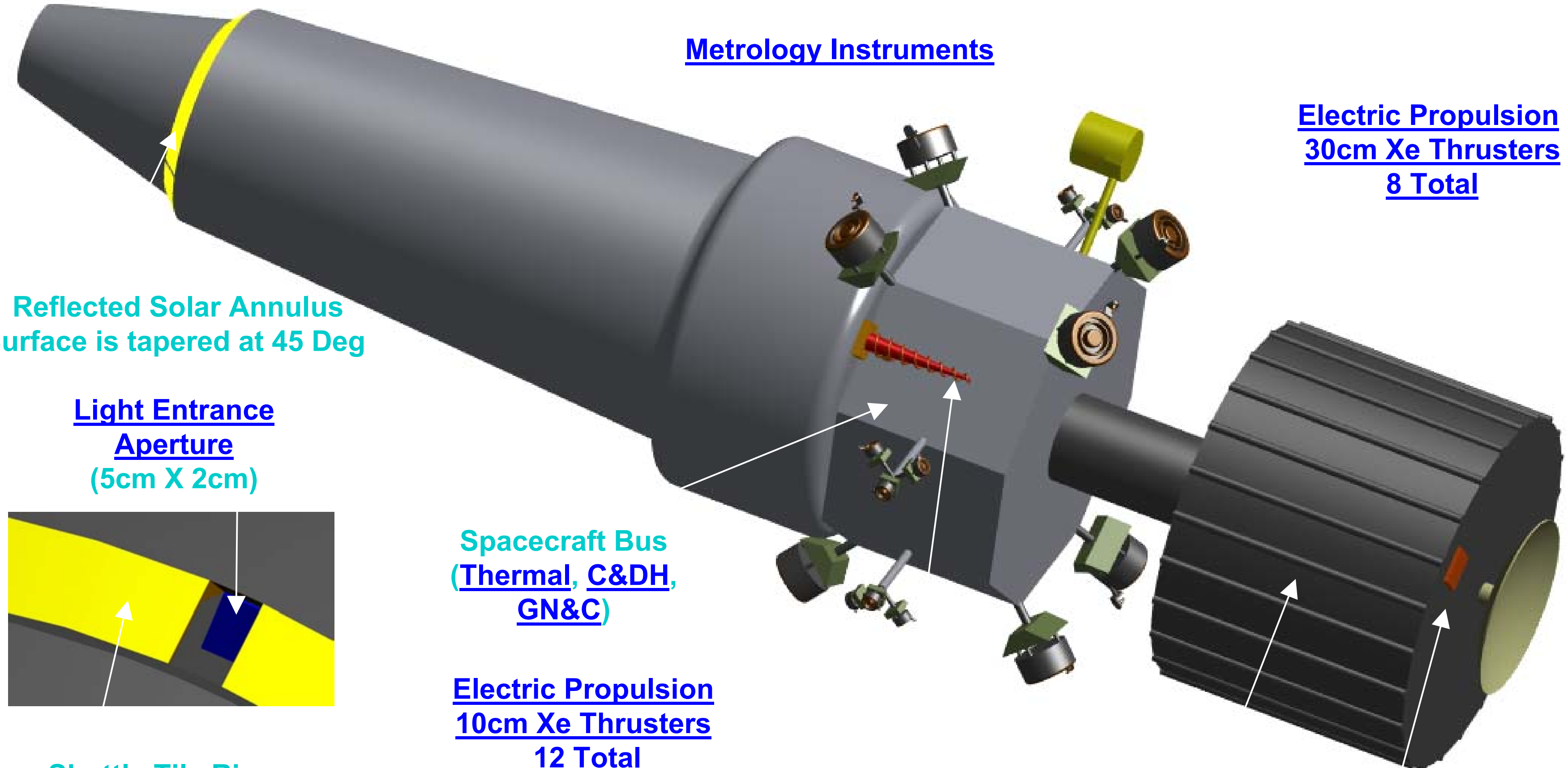
Observatory Architecture



- 25m Aperture primary membrane mirror combined with a secondary Science telescope located 125 m away in formation flying configuration
- 10 year science operations objective without resupply
- 24/7 100% duty cycle

Science Telescope Spacecraft

Patch Antenna



Metrology Instruments

Electric Propulsion
30cm Xe Thrusters
8 Total

Reflected Solar Annulus
Surface is tapered at 45 Deg

Light Entrance
Aperture
(5cm X 2cm)

Shuttle Tile Ring

Spacecraft Bus
(Thermal, C&DH,
GN&C)

Electric Propulsion
10cm Xe Thrusters
12 Total
(Boom Length = 35cm)

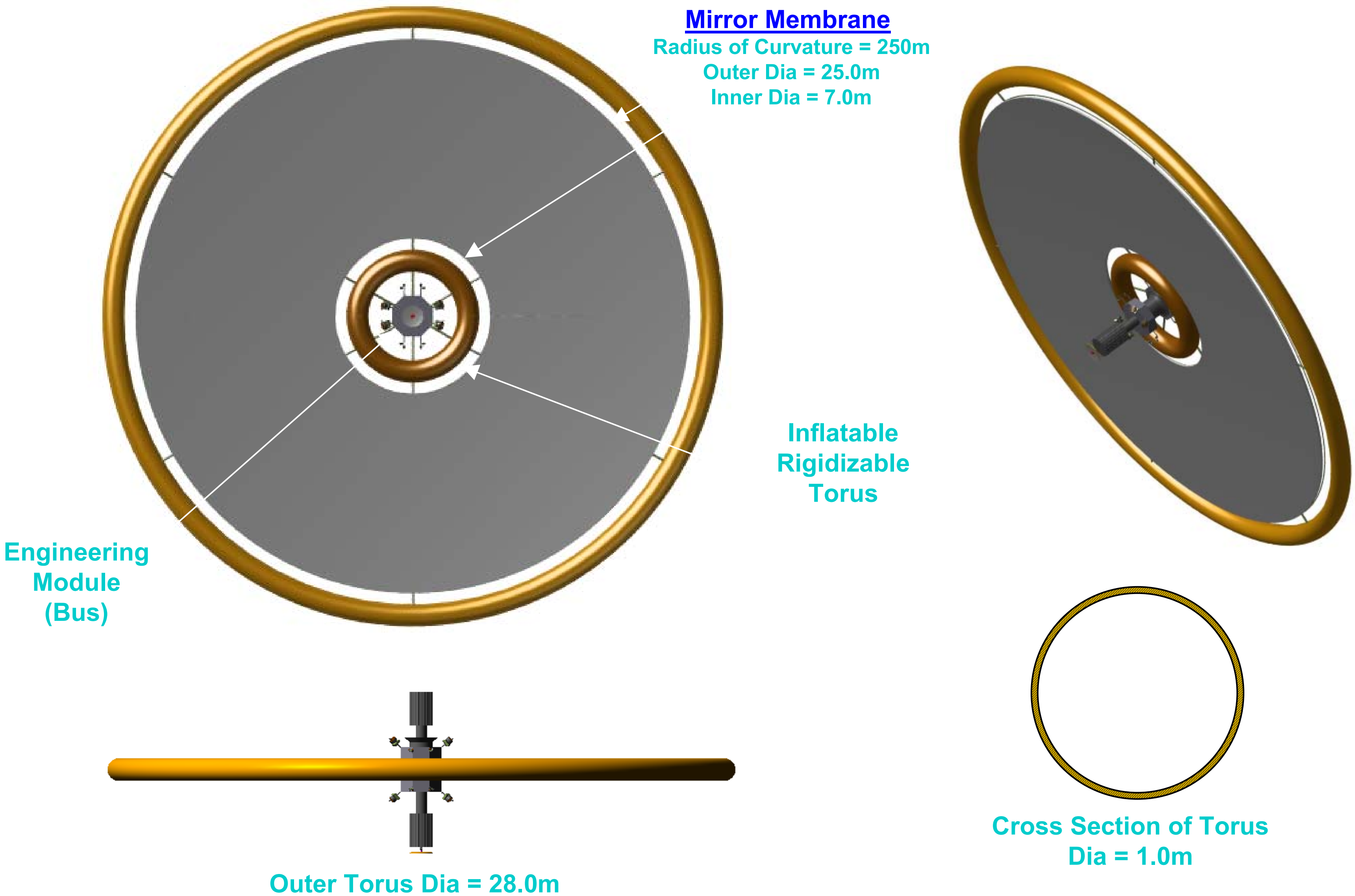
Cylindrical Radiators
And Power System

Quadrafilar Helix Antenna

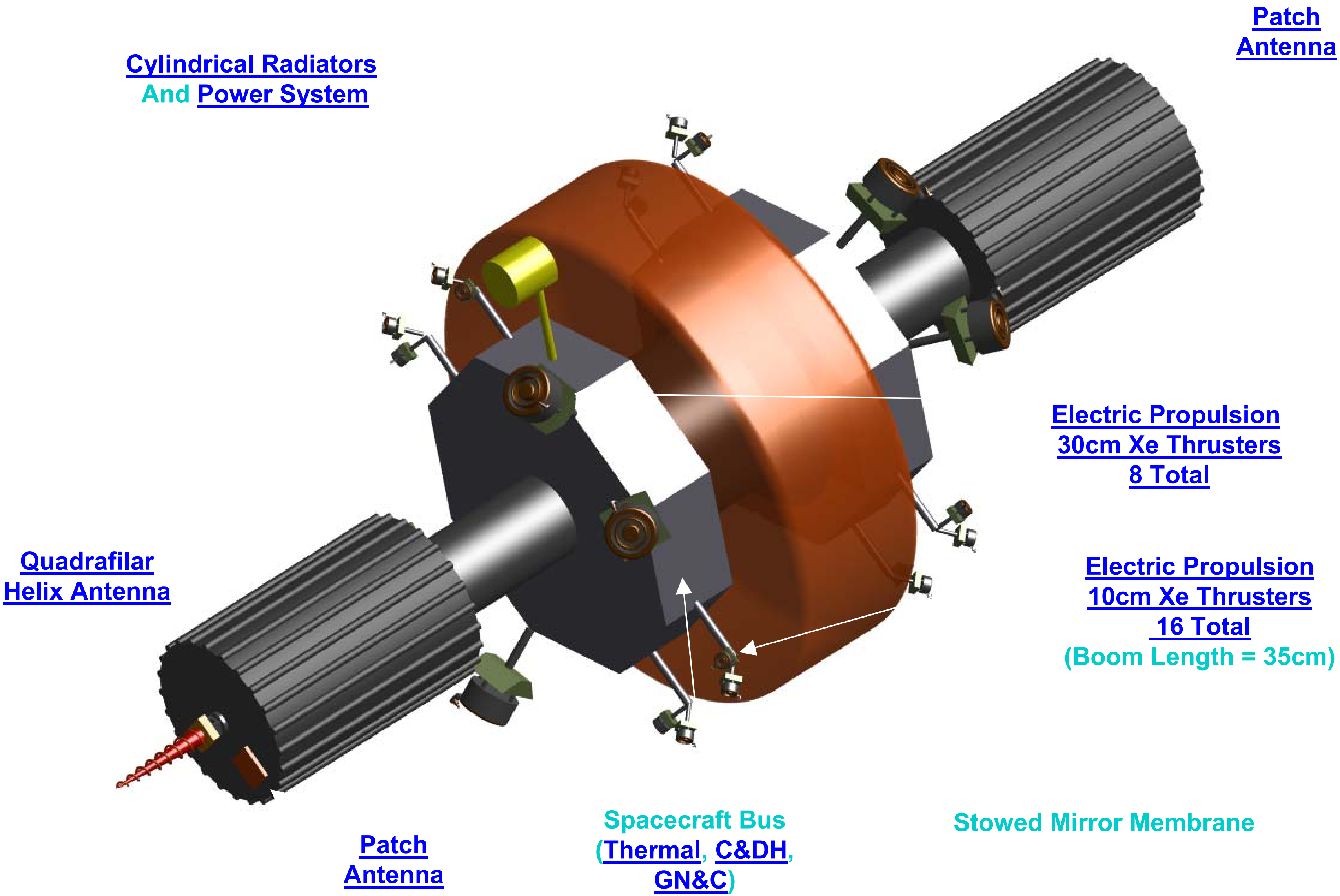
Dish Antenna

Patch Antenna

Aperture Spacecraft - Deployed



Aperture Spacecraft – Pre-Deployment



Baseline Transfer to Earth-Sun L2

- **The observatory will be deployed in a small amplitude libration point orbit about Earth-Sun L2**

- **Transfer from Earth to the small amplitude libration point orbit would take ~5-6 months (with a Lunar swing-by)**

- **The Science and Aperture spacecraft will use their low thrust electric propulsion systems to attain the mission orbit (same system to be used for station-keeping)**

- **Transfer from the small amplitude libration point orbit to the mission orbit will require ~3 additional months and will require a delta V of ~100 m/s**

Summary

- A concept for an Earth observing capability at the Earth-Sun L2 was developed
  - Study Earth's atmosphere as it occults sunlight
- Powered "orbit" near L2 is needed to maintain observatory position within the annular eclipse
  - Must stay within 200 km of the Sun-Earth line
- 25m Aperture primary membrane mirror combined with a secondary Science telescope located 125 m away in formation flying configuration
  - 10 year science operations objective without resupply
  - 24/7 100% duty cycle
- ELV transfer from Earth using a Lunar swing-by to a small amplitude libration point orbit about L2, then a low thrust transfer to the mission orbit using spacecraft propulsion systems
- Key technologies include lightweight membrane structures

Backup

Study Team Organization

LaRC
Science

Overall study integration was provided by Jeff Antol at LaRC. Technical Integration Support was provided by Dr. Ram Manvi of JPL .

NASA Centers
Technical Support

JPL
Principal Architect

- LaRC
- GSFC
- GRC

Ed Mettler at JPL was the Principal Architect. He developed the Telescope Concept to meet the Science Requirements developed at LaRC by Dr. Joe Zawodney. A number of professionals from NASA Centers made significant technical contributions toward the ESL2 Telescope design

Study Team

- Principal Eng. Invest.
- Ram Manvi – Technical Integration
- Ahmet Acikmese – Controls/Dynamics
- William Breckenridge – System Reqs
- Serge Dubovitsky – Optical Metrology
- Steve Macenka – Optical Design
- Eldred Tubbs – Form. Flying/Metrology

- Ken McCaughey

Back to Study Team Organization

Monitor Changes

- **Monitor changes in Chemical Composition and Dynamics of the Earth's Atmosphere**
- **Problem: While changes in the global distribution of radiatively important species are being measured, dynamical changes are not.**
- **Requirements: Measure distribution of O3, CO2, H2O, & aerosols. Derive age of air. Infer dynamics near the tropopause using tracer-tracer relationships.**

Understand Mechanisms

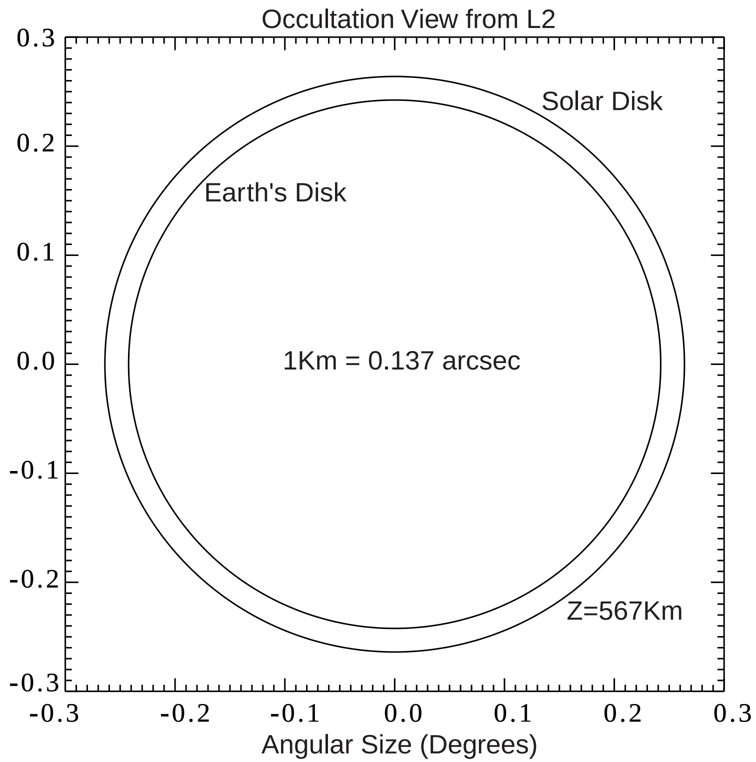
- **Understand the mechanisms of change and quantify the attribution of change**
- **Problem: Lack of suitable data limits the ability to separate direct chemical (forcing) from dynamically driven (feedback) change**
- **Requirements: Fine scale observations and trending of trace species (CLx, NOx, …) as well as dynamical drivers over a solar cycle.**

Improve Predictions

- Improve the short and long term predictive capability of weather and climate models
- Problem: Some physical processes are still unknown and others are poorly quantified or lack suitable density (timeliness) of data.
- Requirements: Provide high spatial density of data promptly for short-term forecasting. Monitor trends in forcing for climate change. Incorporate new mechanisms into models.

Why Occultation from L2?

- **Solar Occultation is best Suited for Long-Term Climate Change Studies**
- **In terms of sampling, L2 is the optimal place to deploy solar occultation instruments.**
- **Provides high vertical and spatial resolution maps twice per day.**
- **Sun is a hot, bright source and the optics will be at very low temperatures: an optimal situation for IR measurements**



Observation Strategy/Orbit

- Remain close (within 200km) to the Earth-Sun axis for 24/7 100% duty cycle.
- Scan around the annular ring of the Earth's atmosphere at least 360 times per day for ~1° "longitudinal" sampling
- Sample each rotation at least 360 times to provide ~1° "latitudinal" sampling
- Refraction will limit the lowest altitude to ~8km
- Co-align all instruments and synchronize operation to provide sampling of the same air mass over all wavelengths (0.38 to 10 microns)

Improvements over Current Practice

- **Spatial resolution can approach 0.1 degrees (10x improvement over Aura) through a combination of increased instrument sampling and algorithmic techniques (tomography).**
- **Trend-Quality observations of the dynamical response of the middle atmosphere (10-70km) to climate change.**
- **Similar capability would require multiple spacecraft in low Earth orbit.**
- **Near Real-Time production of final products for time-critical consumption (forecast models)**

Design Drivers (cont)

- Mass and Power constraints:
  - Compact designs that share optics
  - Passive thermal control
  - Innovative design for Mid-IR instrument
- High bandwidth and continuous operation:
  - Optical link to LEO relay?
- Low latency end-to-end data system:
  - Straight-pipe data system & minimal buffering
  - Verified Real-Time algorithms prior to launch

Visible Spectrometer Concept

- Imaging spectrometer based on the Offner design covering 380 to 980nm.
- Dual 512 x 512 element Active Pixel Sensor arrays operating up to 100Hz.
- 0.6 nm spectral sampling
- Each 60 um square pixel maps to a 1 km square footprint at the Earth’s limb.
- 16-bit ADC operating at up to 26MHz.
- 8.4 Mbps minimum continuous data rate

NIR Spectrometer Concept

- Imaging spectrometer based on the Offner design covering 980 to 2480nm.
- Dual 512 x 512 element Active Pixel Sensor arrays operating up to 100Hz.
- 1.5 nm spectral sampling
- Each 60 um square pixel maps to a 1 km square footprint at the Earth’s limb.
- 16-bit ADC operating at up to 26MHz.
- 8.4 Mbps minimum continuous data rate

Mid-IR Concepts

- A broad-band spectrometer covering 2.5 to 10 µm for major absorbers and narrow-band high resolution Imaging FTS (DASI derivative) for minor trace species.
- MEMS cantilever bolometer and/or multi-color array detectors
- Passive cooling
- Real-time processing of IFTS data in FPGA
- Allocated 8.4 Mbps data rate

System Trades

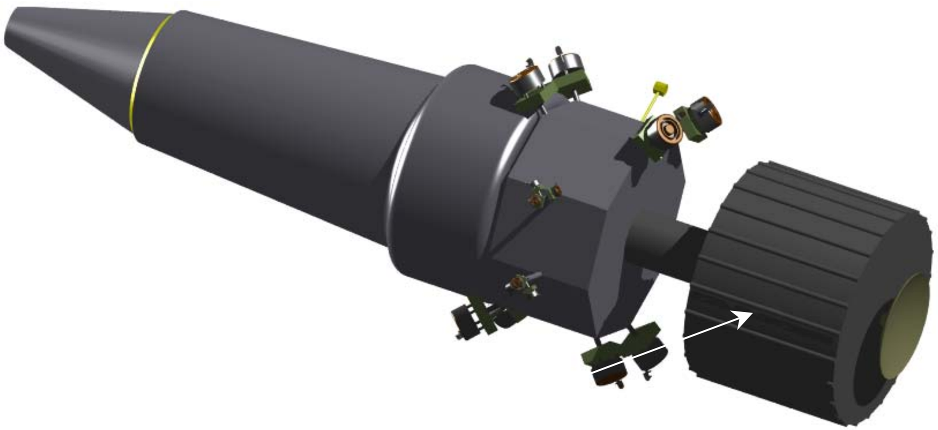
- Sparse vs. filled aperture as it impacts sampling
  - Filled aperture required to meet 1° spatial sampling
- Active "orbit" control vs. Halo orbit
  - Active control provides 24/7 operation with twice daily maps
- Mass & Power constraints favor fewer/smaller instruments
  - Technology development of Multi-color detectors & instrument designs that employ them would reduce mass by at least 2x
- On-Board processing vs. High Bandwidth Down-link
  - Science community favors retention of Raw Level-0 data
  - No clear winner in terms of power consumption

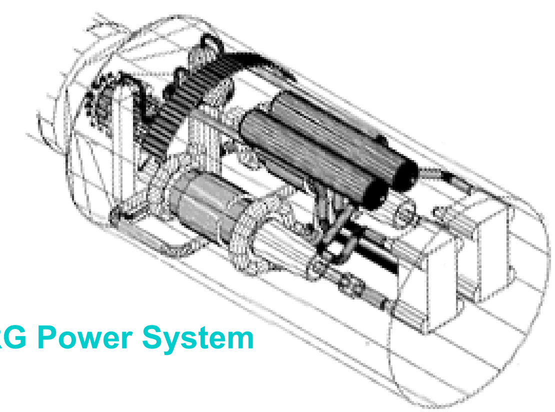
Trades and Alternatives

- Gas Filter Correlation vs. Broadband Radiometer vs. Imaging FTS for the Mid-IR
  - Lifetime & mass issues of GFCR
  - Sensitivity and selectivity of broadband devices
  - Development of a fast Imaging FTS
- Question remains open as to whether an L2 mission can be more cost effective than a few LEOs
  - Are SABRE, MLS, DIAL, or HRDLS –type approaches capable of trend quality measurements?

Science Spacecraft Power System

- Requirements
  - **3 kWe for spacecraft bus, instruments, and thruster operation**
  - **100 % Duty cycle required**
  - **Mission duration 10 years**
- Radioisotope Power Source (RPS) selected as best option
  - **Stirling Radioisotope Generators (SRG) with output of 3000We**
- Also assessed photovoltaic (PV) array option
  - **Size of PV array makes integration difficult and interferes with aperture**

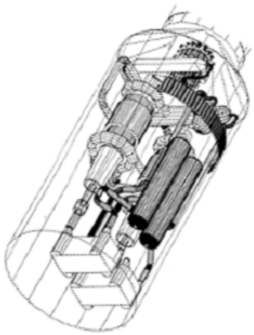




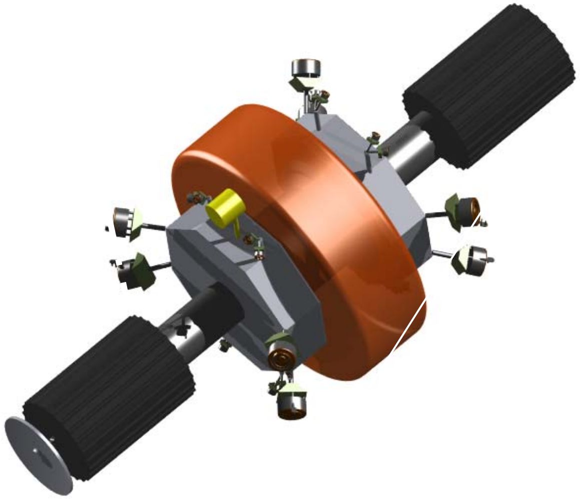
SRG Power System

Aperture Spacecraft Power System

- Requirements
  - **2 kWe for spacecraft bus and thruster operation**
  - **100 % Duty cycle required**
  - **Mission duration 10 years**
- RPS selected as best option
  - **SRG with output of 2000We**
- Also assessed PV array option
  - **Array on Aperture spacecraft interferes with thruster operation.**



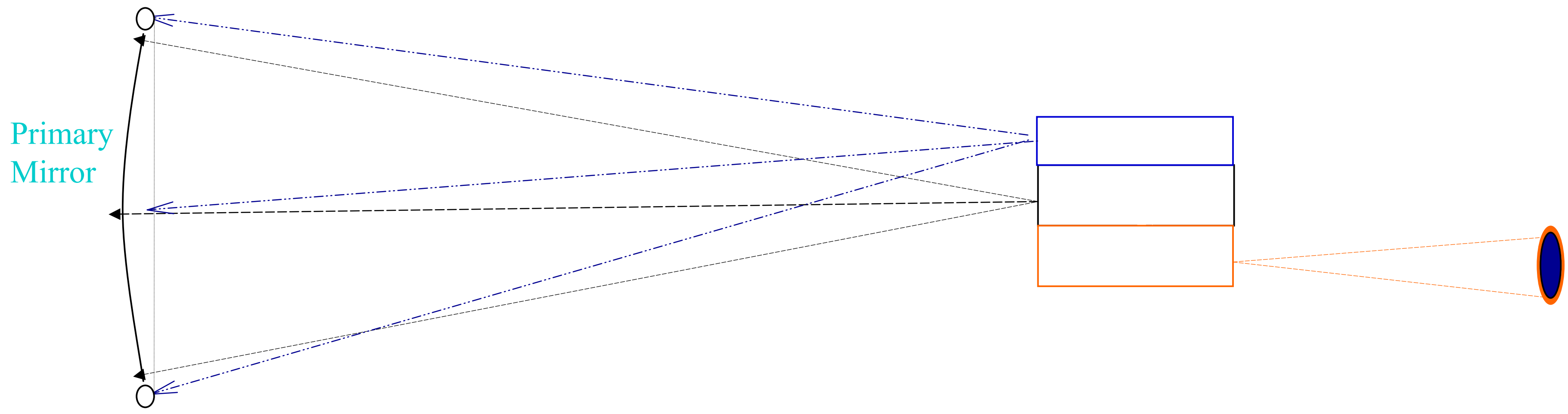
SRG - Power System



Cylindrical Radiators
And Power System
(Length = 1.5m, Dia = 1m)

Back to Aperture Spacecraft

Metrology Platform on Science S/C



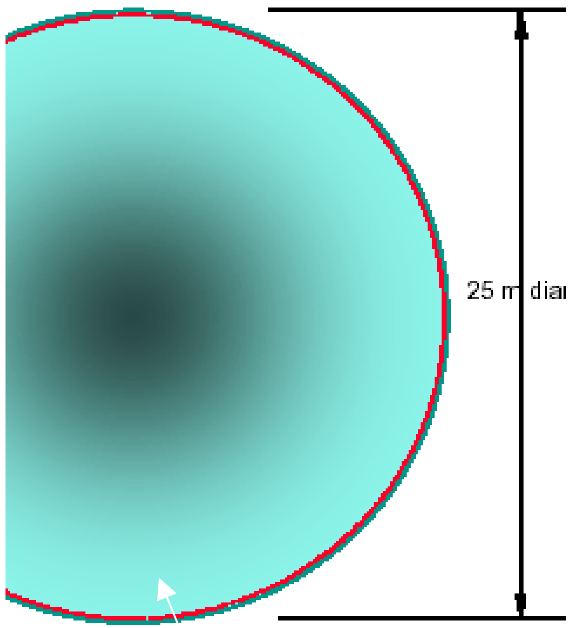
GPS-like range and phase measurement between transmitter and receiver, triangulated to get relative position and attitude of the Aperture S/C for acquisition and coarse formation control.

Laser range & bearing to retro-reflectors on the mirror to get precision relative location and attitude and mirror shape for fine formation control and Earth image location prediction.

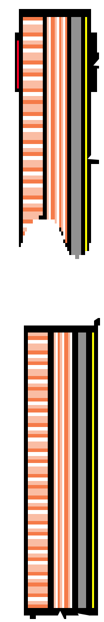
Image Earth & Sun to find points on the limbs and determine relative Earth direction, position offset from the Earth-Sun line and coarse Earth range.

Back to Science Spacecraft

Membrane Primary Mirror



Primary Mirror



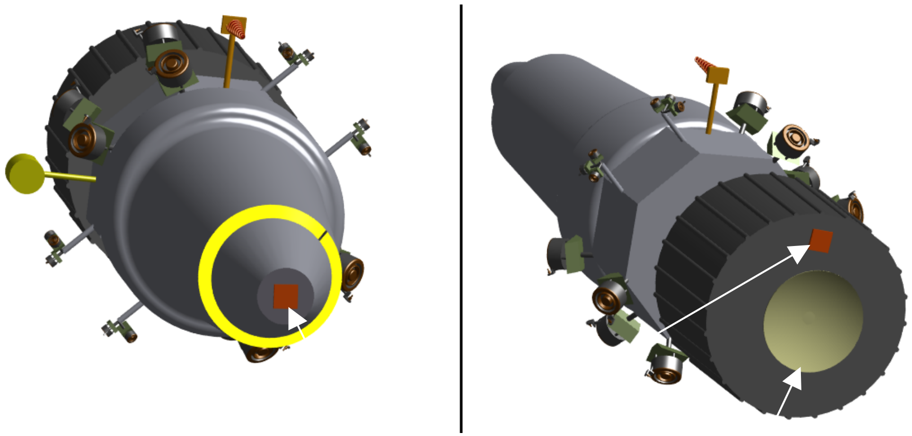
* E-H Yang and S-S Lih, JPL , 2003 IEEE, 0-7803-7651-X/03

Back to Aperture Spacecraft

Science Spacecraft Comm System

- X-Band telemetry transceiver (QPSK modulation, operating at ~100 MBPS)
  - **100 Watt X-band RF Power Amplifier, ~ 50% efficiency) = 200 Watts of Power**
  - **1 meter inflatable antenna (.53kg/m^2), including feed; add gimbal**
- S-Band transceiver for commands and health/status telemetry
  - **3 watt RF output --> requires about 15 watts**
  - **S-band patch dipole antenna (two) for coverage**
- UHF transponder for crosslink communications with Aperture spacecraft
  - **110-200 Milliwatt transmit power**
  - **Total of ~ 15 Watts of power**
  - **Quadrafilar Helix antenna**

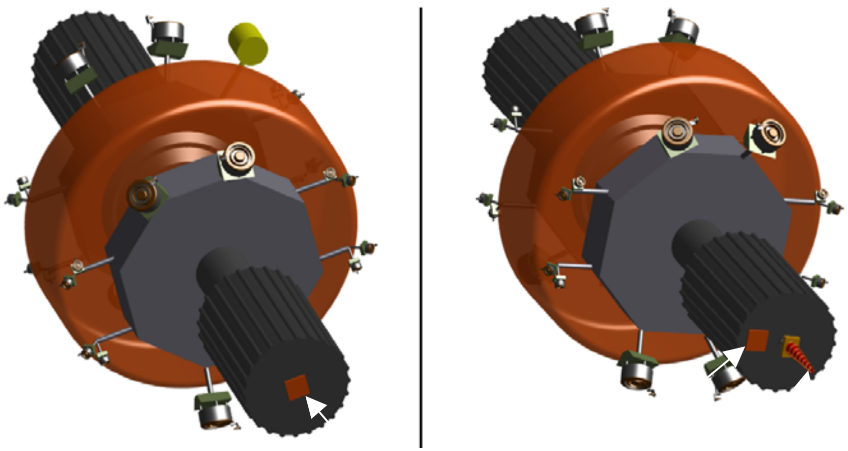
- Telemetry ground stations at SvalBard, Norway and McMurdo, Antarctica
  - **X-Band Antennas (11.3 m and 10m respectively, dual X,S capability)**
  - **Command transmission to Spacecraft directly (during transit) and via Earth L4/L5 relay(s) during operations.**
  - **X-band QPSK reception @ 50 Msps; effective data rate of 100 Mbps**
  - **Downlink coverage time (8.1 hours/day)**



Back to Science Spacecraft

Aperture Spacecraft Comm System

- S-Band transceiver for commands and health/status telemetry
  - **3 watt RF output --> requires about 15 watts**
  - **S-band patch dipole antenna (two) for coverage**
- UHF transponder for crosslink communications with Science spacecraft
  - **Milliwatt transmit power**
  - **Total of ~ 15 Watts of power**
  - **Quadrafilar Helix antenna**
- Ground Stations at SvalBard, Norway and McMurdo, Antarctica
  - **S-Band Antennas (11.3 m and 10m respectively) for commanding**
  - **Transmission to Spacecraft directly (during transit) and via Earth L4/L5 relay during operations (if necessary).**



Back to Aperture Spacecraft

Propulsion System

- Large thrusters for primary station-keeping thrust to keep spacecraft in position (radially) for observation
  - **1.30 kW each for maximum operation of 2 engines**
  - **Maximum thrust of 70 mN**
  - **Isp = 9200 seconds, 90% efficiency**
- Small thrusters for fine control per telescope requirements
  - **250 W each for maximum thrust of 2.7 mN;**
  - **Isp = 8700 seconds, 90% efficiency**
- Thruster type: primarily Gridded Ion engines
  - **Best choice for high specific impulse (propellant-limited) missions**
  - **However, in Current Best Estimate case, Hall thrusters probably best choice for aperture spacecraft primary thrusters because of relatively low specific impulse**
- Thrusters mounted on gimbals to enable some local pointing control
  - **Reduces demands on spacecraft orientation required to maintain proper thrusting**
- Redundancy enabled by:
  - **Shifting thruster use to other devices in event of failure**
    - **Vehicle operations will have to be changed to maintain thrusting capability**
    - **Dedicated power processing and propellant management systems on each large**

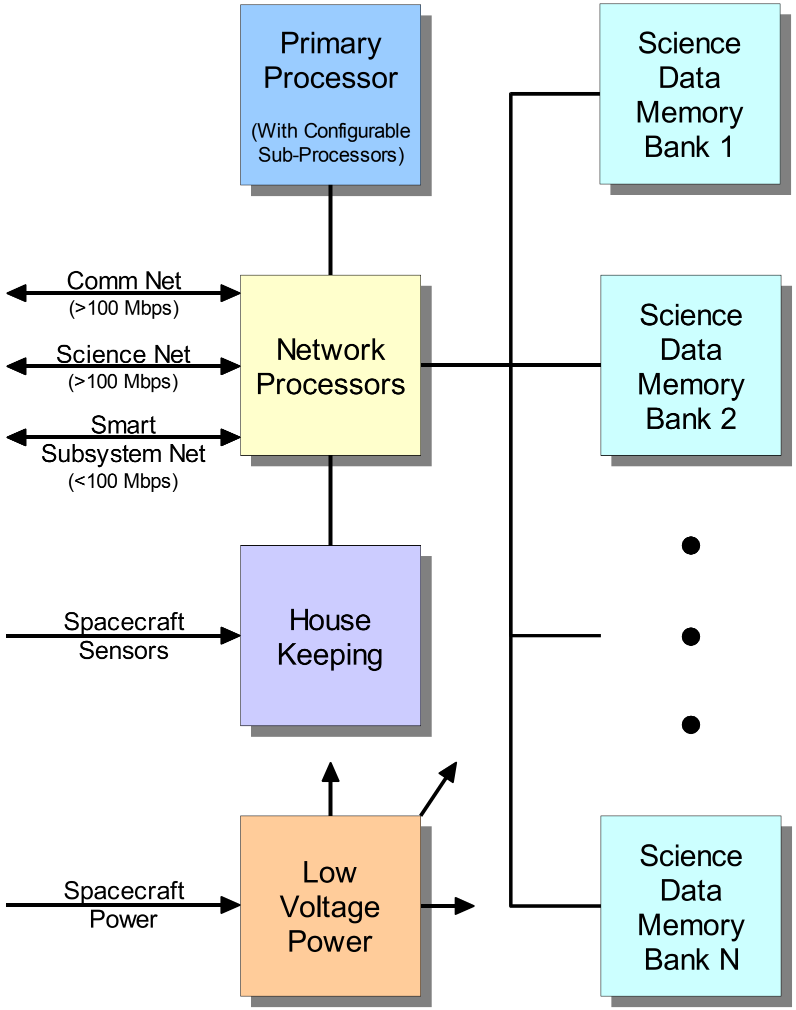
Thermal System

- Aperture Spacecraft
  - **7 meter hole in aperture prevents thermal gradients in mirror surface**
  - **Heat from SRG's can warm engineering module by loop heat pipes. Engineering section needs 140 watts of heat.**
  - **SRG radiators can dissipate 5000 watts (total) at 60ºC.**
- Science Spacecraft
  - **1" thick Shuttle Tiles insulate aperture disk from intense heat from mirror. Tile surface = 845ºC. 44ºC substructure temperature.**
  - **Aperture slit (10cm^2) allows 280 watts of heat to enter.**
  - **Mirror #1 needs to be conductively cooled by heat pipe or heat strap.**
  - **Science instruments need 185 watts of heat for 20ºC.**
  - **Bus needs 150 watts of heat. Supplied from loop heat pipe network from SRG radiator.**
  - **SRG radiator can dissipate 5700 watts at 60ºC.**

Back to Science S/C   Back to Aperture S/C

Science Spacecraft C&DH

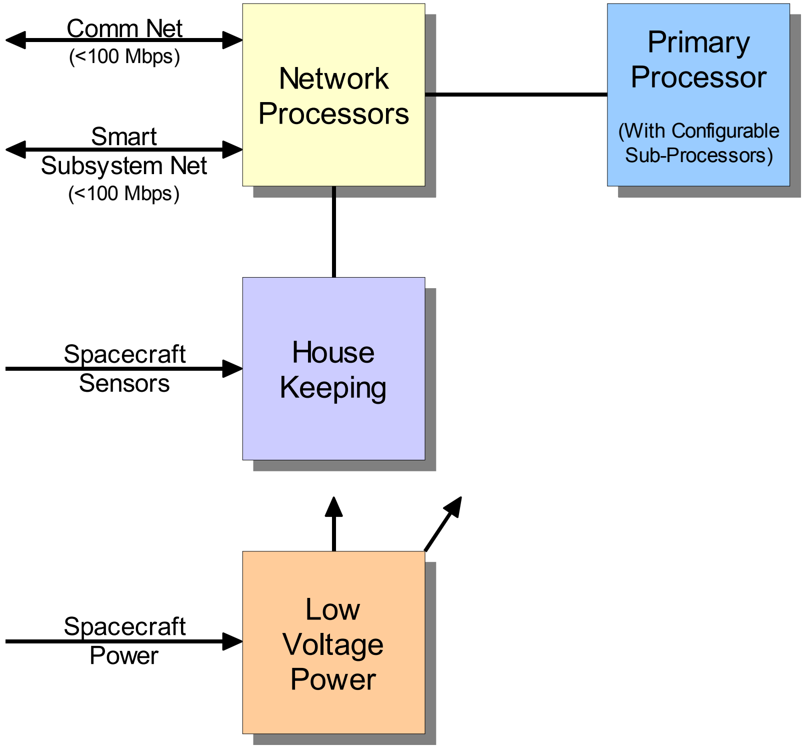
- Fully redundant (one string shown)
- Uses system-on-chip technology
- Memory banks can be powered down when not needed
- Separate dedicated networks for different functions
- Smart subsystems will reduce C&DH mass & power
- Configurable sub-processor provides for adaptability
- Dedicated local networks to save power
- Scalable design
- Science data rate (2.2Tbit/day)
  – C&DH data storage baseline ~2.2Tbit



Back to Science S/C

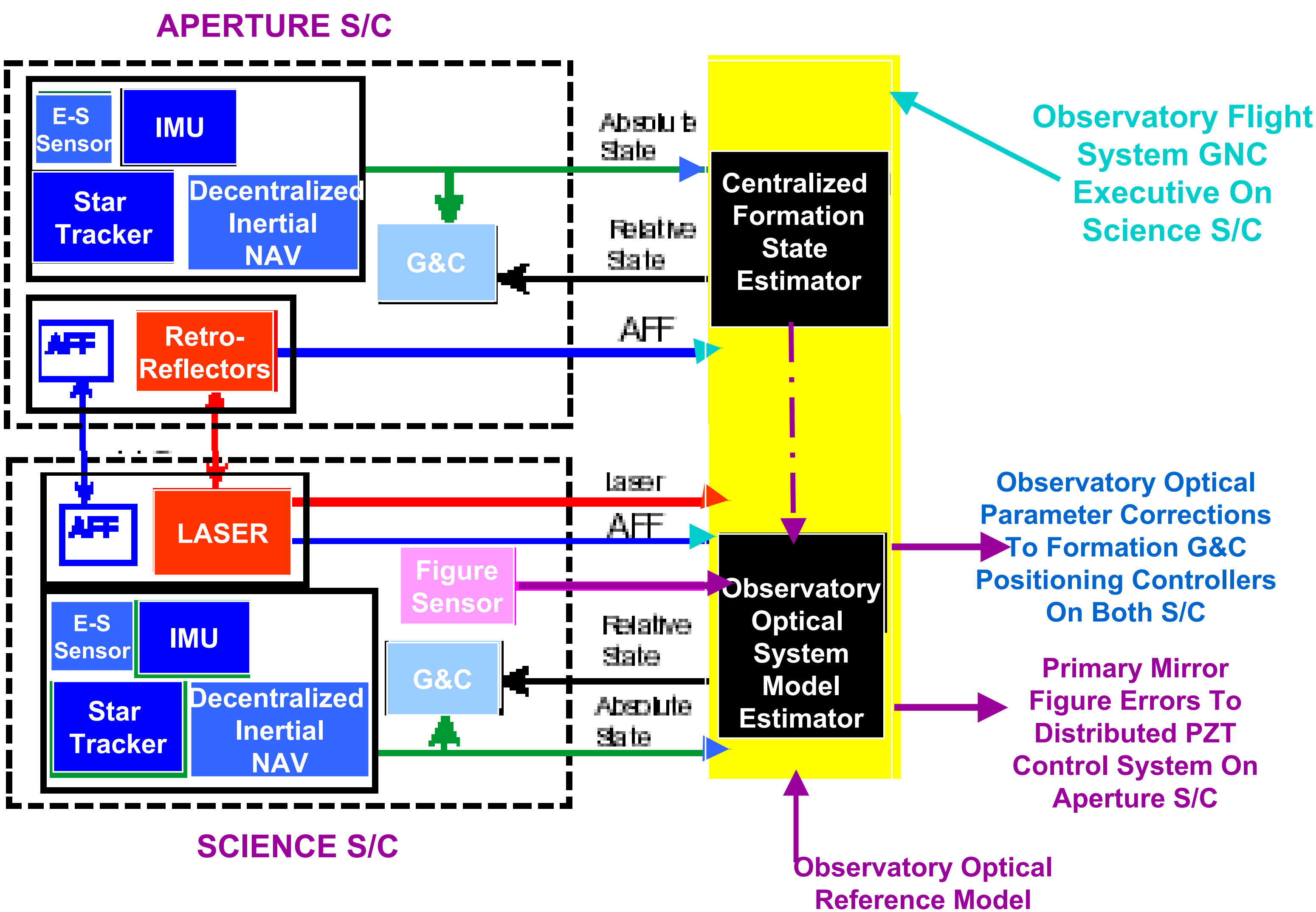
Aperture Spacecraft C&DH

- Scaled down from science spacecraft reusing major components
- Fully redundant (one string shown)
- Uses system-on-chip technology
- Separate dedicated networks for different functions
- Smart subsystems will reduce C&DH mass & power
- Configurable sub-processor provides for adaptability



Back to Aperture S/C

Formation GNC Concept



Back to Science S/C   Back to Aperture S/C

- **Navigation during the transfer from the small amplitude libration point orbit to the mission orbit may be challenging if orbit determination arcs need to include low thrust periods and would require data from spacecraft sensors (for example, optical sensor, IMU) in addition to DSN tracking data**
- **Small amplitude libration point orbit should require stationkeeping app. every 3 months in the event deployment is delayed (more stable than mission orbit)**
- **After the mission orbit is attained frequent stationkeeping maneuvers will be required**

Optics Design Drivers

- Primary Aperture is 25 m diameter to satisfy science 1 km resolution at Earth over broadband spectrum, i.e., Diffraction limit of 67 micro-radian at 10.5 microns. Theoretical size is 19 m with added margin for membrane boundary conditions.

- Earth-Sun are extended objects viewed from L2 and require a Spherical Aperture system or *Schmidt Telescope* concept to handle wide angle and high resolution

- Separated S/C optics are required by the desired Primary f/10 focal ratio (to minimize aberrations) with 250 m focal length and 500 m center of curvature (c-c).

- The *Schmidt* spherical aberration Corrector Mirror, normally located at the (c-c) in a monolithic system, must be re-imaged to locate inside the secondary (Science) S/C Telescope. This is called a "Reduced Schmidt" design and adds complexity.

Optics Design Drivers (cont)

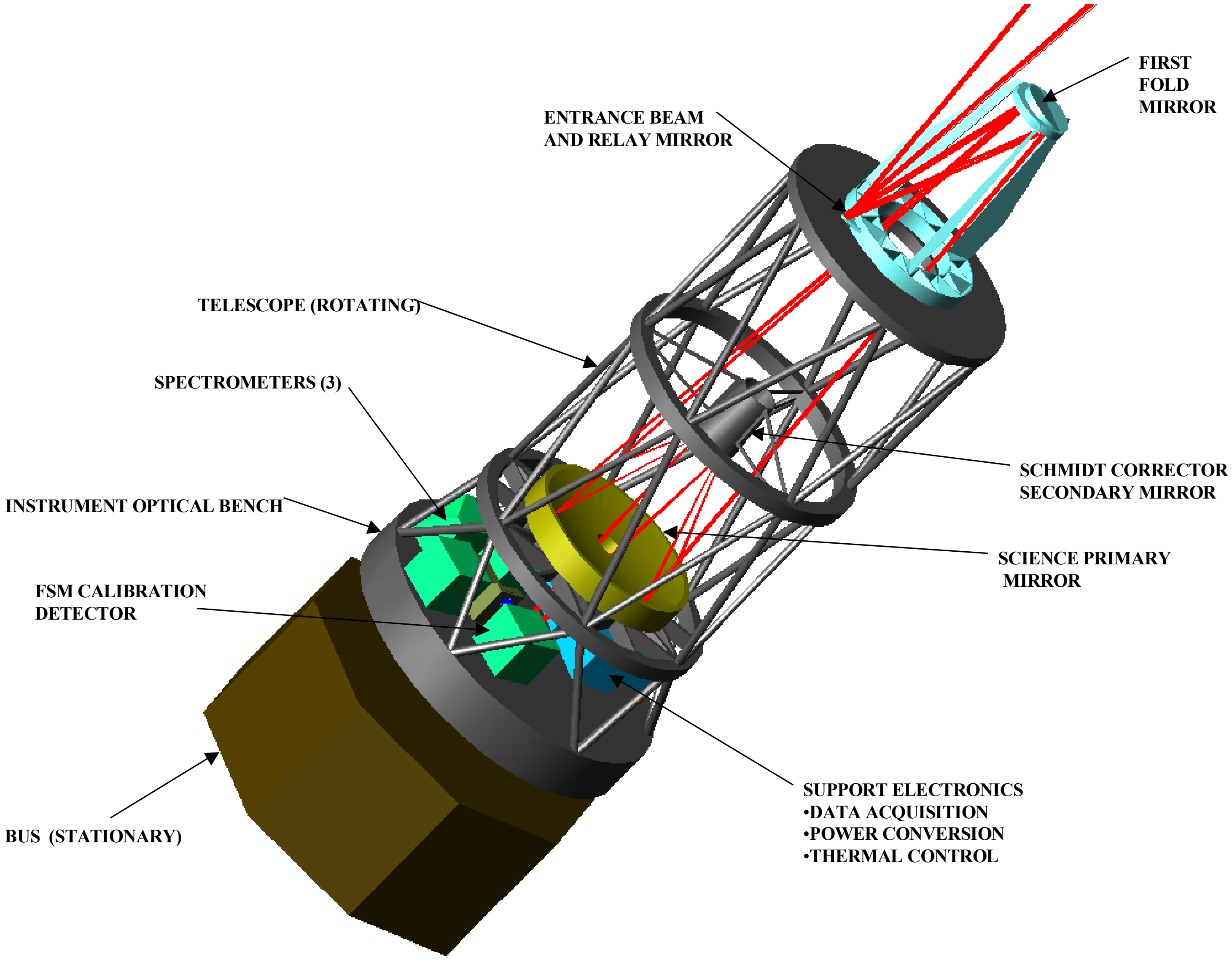
excessively large

The f/5 mass is < 1/10 th the f/10 Telescope.

Optics Implementation Trades

- extremely large and massive,
  powered orbit near L2

Science Telescope Optics Design

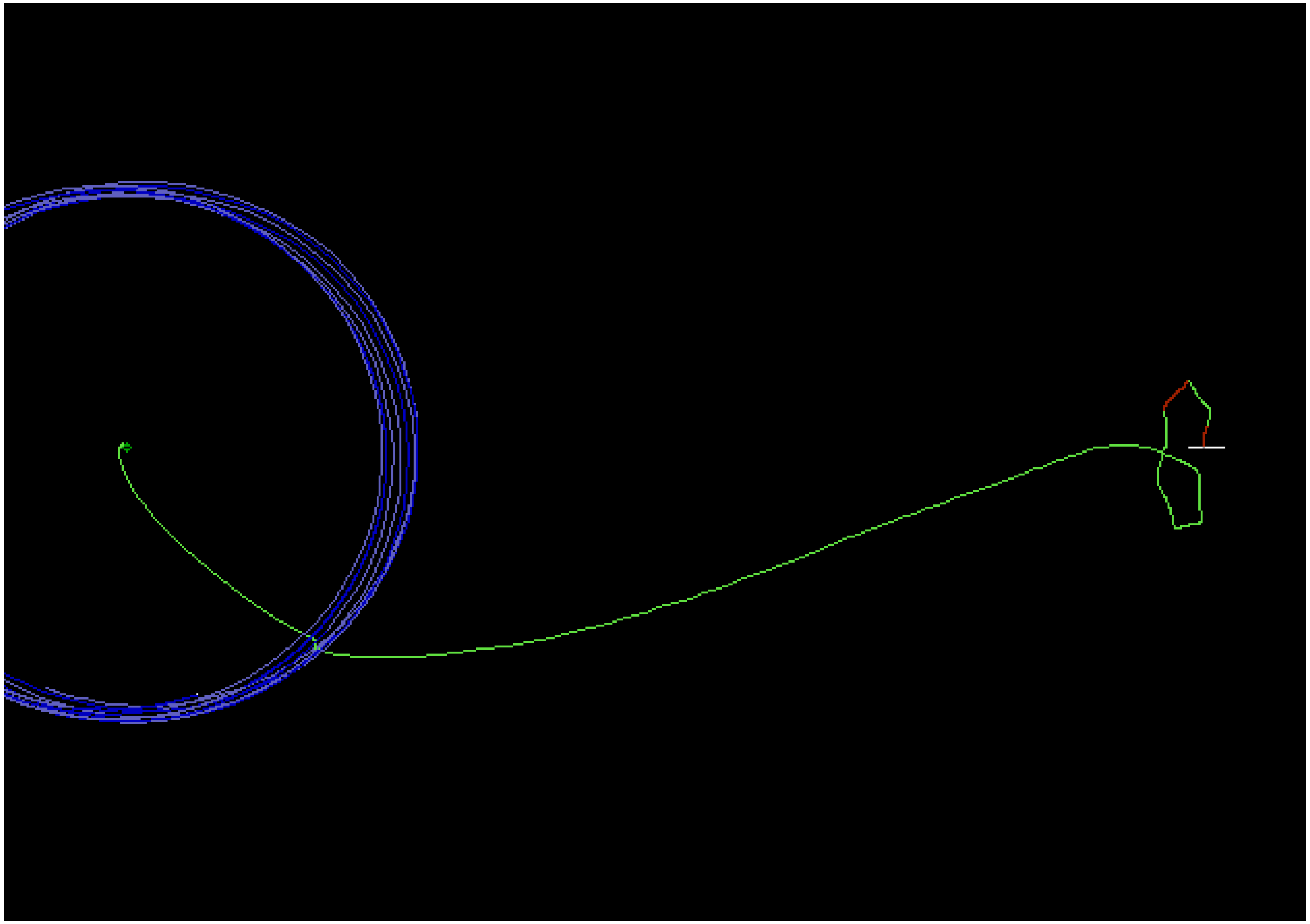


Delivery to Earth-Sun L2 Mission Trades

- **Baseline**
  - ELV transfer from Earth using a Lunar swingby to a small amplitude libration point orbit about L2, then a low thrust transfer to the mission orbit using spacecraft propulsion systems
- **Alternative #1**
  - Impulsive Earth escape, then low thrust using a Solar Electric Propulsion (SEP) stage to the L2 point, and final impulsive zero velocity deployment using hybrid Chemical / SEP Carrier Vehicle
- **Alternative #2:**
  - Launch to LEO, rendezvous/docking with a Nuclear Electric Propulsion (NEP) stage and then low thrust transfer to the L2 point

Sample Transfer Trajectory from MAP Orbit with Lunar Swingby to Mission Orbit

(low thrust periods in red using a thrust/mass ratio which approximates the minimum required for stationkeeping)



SEP Transfer to Earth-Sun L2

- A direct transfer trajectory using Solar Electric Propulsion (SEP) was briefly analyzed

- Large amplitude L2 libration point orbit would not require a Lunar swingby but would require a launch vehicle C3 of app. –0.6 km^2/s^2 and an increased delta_v for transfer from the large amplitude libration point orbit to the mission orbit

- However, as the assembly approaches the target orbit it will enter Earth shadow (apparently for some time) and decrease the Solar array power available for the SEP thrust.
  - Both spacecraft would need to be deployed prior to Earth shadow entry to complete the final portion of the trajectory using their propulsion systems

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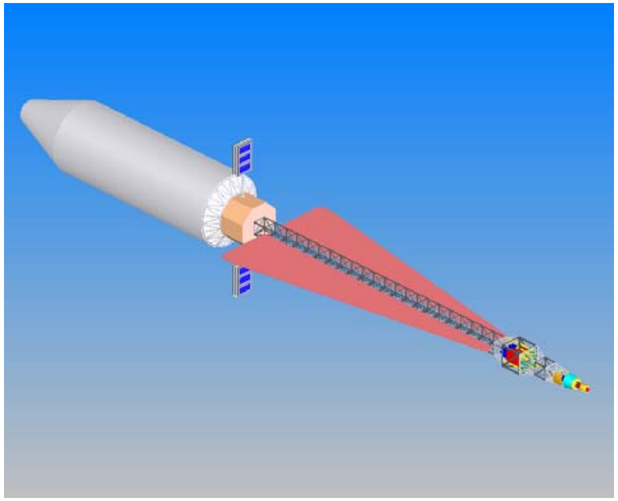
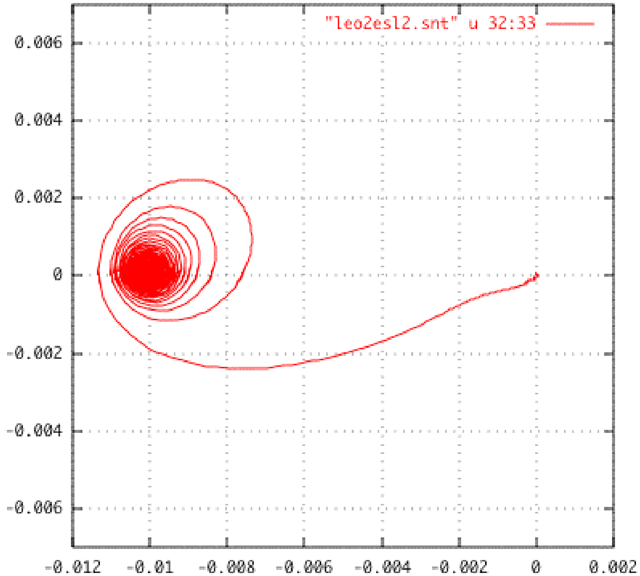
NEP Transfer to Earth-Sun L2

- **Direct low thrust transfer to Earth/Sun L2 (ESL2)**
- **Use Low thrust (NEP) stage to transfer the Observatory from Earth to the ESL2 point**
  - L2 telescope delivered to LEO of 1000 km by Delta IV H and docked with NEP transfer stage in orbit
  - NEP Transportation Stage assumed to be already on-orbit, previously delivered to Nuclear Safe LEO (1000 km)
- **Time to ESL2 arrival = 494 days**





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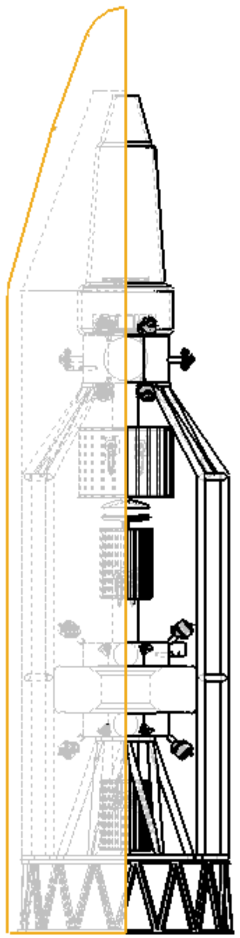
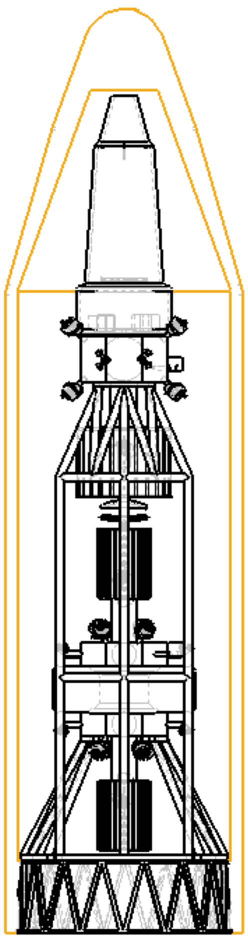
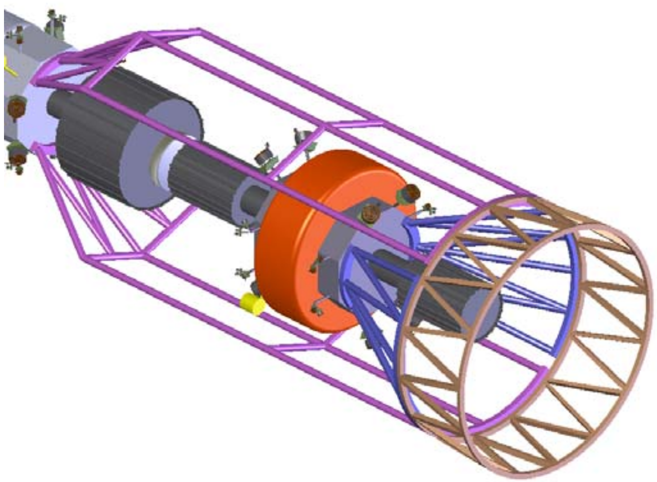
Launch Vehicle Packaging







Enabling Technologies

- Miniaturization of Subsystems hardware and science instruments, 3-D electronics, integrated structures/cabling, MEMS sensors and actuators
- Instrument and algorithm technologies
  - Detectors
  - Tomography
- Building of deployable large, low areal density mirrors and their associated structural components for operation at Earth-Sun L2 Environment
- Robust end-to-end modeling of telescope system and validation of system model
- Structures and Control
  - Active Figure Control Concept for Membrane Primary Mirror
  - Lightweight composite structural materials for Telescope and Spacecraft
- Power
  - Advanced Radioactive Isotope Power Sources with high specific power efficiency

Enabling Technologies (cont)

- **GN&C**
  - Combined High Accuracy Earth-Sun Sensor to maintain Orbit Tracking
  - RF and Laser-Optical Metrology Systems for Formation 3-D Knowledge
  - Precision Formation Flying and Orbit Navigation Methodologies

- **Propulsion and Control**
  - Advanced high specific-impulse linear Xe EP thrusters in large/small sizes
  - Sophisticated, higher-order station-keeping controllers that mitigate thruster limitations

- **Packaging & Deployment**
  - Packaging for delivery of the primary mirror to Earth-Sun L2, and logistics of its deployment